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FRICITION AND WEAR OF TITANIUM ALLOYS
AND COPPER ALLOYS SLIDING AGAINST
TITANIUM - 6-PERCENT-ALUMINUM -
4-PERCENT-VANADIUM ALLOY IN AIR AT 430° C

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16. Abstract <p>Experiments were conducted to determine the friction and wear characteristics of aluminum bronzes and copper-tin, titanium-tin, and copper-silver alloys sliding against a titanium - 6-percent-aluminum - 4-percent-vanadium alloy (Ti-6Al-4V). Hemispherically tipped riders of aluminum bronze and the titanium and copper alloys were run against Ti-6Al-4V disks in air at 430° C. The sliding velocity was 13 cm/sec, and the load was 250 g. Results revealed that high-tin-content titanium and copper alloys underwent significantly less wear and galling than commonly used aluminum bronzes. Also friction force was less erratic than with the aluminum bronzes.</p>				13. Type of Report and Period Covered Technical Note	
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FRICITION AND WEAR OF TITANIUM ALLOYS AND COPPER ALLOYS SLIDING
AGAINST TITANIUM - 6-PERCENT-ALUMINUM - 4-PERCENT-
VANADIUM ALLOY IN AIR AT 430⁰ C

by Donald W. Wisander

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SUMMARY

Friction and wear experiments were conducted with various titanium and copper alloys sliding against a titanium - 6-percent-aluminum - 4-percent-vanadium alloy (Ti-6Al-4V) in 430⁰ C air. Hemispherically tipped rider specimens of the titanium and copper alloys were run in sliding contact with Ti-6Al-4V disks at a velocity of 13 centimeters per second and a load of 250 grams. Durations of tests were 5 to 6 hours.

Results revealed that titanium-tin and copper-tin alloys with high tin content had significantly lower wear than the aluminum bronzes (baseline materials). Aluminum bronze showed a tendency to gall, whereas the high-tin alloys did not. Cast Inconel (600), while having lower wear than aluminum bronze, still tended to gall. Friction coefficients of all combinations varied from about 0.2 to 0.35. High-tin alloys formed a transfer film on the Ti-6Al-4V, and subsequent back transfer of material to the rider may have masked the wear.

INTRODUCTION

Some parts of aircraft engines are in sliding contact at relatively high temperatures; an example is the air bleed mechanism, which is exposed to temperatures as high as 430⁰ C (700 K). For such applications titanium alloys are attractive because of their high strength-weight ratios and good high-temperature mechanical properties. However, their friction properties are generally recognized as a problem area. For example, references 1 and 2 report that titanium, titanium-aluminum alloys, and titanium-tin alloys sliding against 440C in vacuum show high friction coefficients (0.3 to 0.6). References 3 to 12 similarly report on the severe galling tendencies and high

friction (friction coefficients >1.0) of titanium and its alloys in air. Also of significance is the lack of improvement of friction and wear properties of titanium on titanium with a wide variety of commonly used lubricants (refs. 1 and 9). Except for the study of reference 8, all data were taken with no external heat supplied to specimens.

Since titanium sliding against itself tends to gall or seize (refs. 1 to 12), designers often resort to the use of a dissimilar metal such as aluminum bronze in sliding contact with titanium. Further, some form of solid film lubricant is often used. One lubricant that is commonly used is an acrylic-bonded molybdenum disulfide (MoS_2), but it has limited life at 430°C . Another lubricant candidate for high-temperature applications is a silicone grease with MoS_2 (Mil L25681C). Experiments described in this report indicated that this lubricant also has a very limited operating life at 430°C in air.

These results indicate the need for either a better solid lubricant or inherently self-lubricating materials. But a problem with thin solid films has been the finite life and the high friction which is associated with film rupture. This friction and wear problem could be mitigated through use of sliding couples that are self-lubricating at 430°C ; and since some of the parts in aircraft are inaccessible for maintenance, it would be desirable to have such self-lubricating alloys that would not require external lubrication (e. g. , periodic application of MoS_2 coatings).

The objectives of this study were (1) to formulate and/or identify material couples that are inherently self-lubricating at a temperature of 430°C in air and (2) to determine if the coefficient of friction is within the range of acceptability (<0.35).

Friction and wear experiments were carried out at 430°C in air. Rider specimens (hemispherically tipped) were run in sliding contact with a rotating disk of a titanium - 6-percent-aluminum - 4-percent-vanadium alloy (Ti-6Al-4V). The disk was run with and without treatments, and the riders (various alloys) were run without treatment. Data were obtained at a sliding velocity of 13 centimeters per second and a load of 250 grams. Sliding experiments using MoS_2 lubricants were conducted to establish a baseline reference to current practice.

APPARATUS AND PROCEDURE

The apparatus used is shown in figure 1. The basic elements were a rotating disk (diameter, 6.35 cm) and a hemispherically tipped rider specimen (diameter, 0.95 cm) in sliding contact. The disk was rotated by an electric motor operating through a spindle-mounted shaft. The rider specimen was loaded against the rotating disk by a deadweight system, the force of which was transmitted through a shaft vertically mounted in porous-metal gas-lubricated journal bearings. The atmosphere was dry air, introduced at the bottom of the chamber as well as through the gas bearings.

The friction force was measured by a dynamometer ring (with strain gages) attached as shown in figure 1, and the strain-gage output was transmitted to a strip-chart recorder. Rotational speed was measured by a magnetic pickup connected to an event counter. Rider temperature was controlled with an infrared pyrometer, which was sighted through a hole in the chamber wall onto the rider specimen just above the rider-disk contact area.

The disk specimens were lapped and polished on 4/0 emery paper. All specimens were scrubbed with levigated alumina and rinsed in tap water and distilled water just before use. The root-mean-square surface finish was 0.1 micrometer.

Specimens were mounted in the test chamber, which was then closed and purged with dried air. The disk was rotated and heated until the specimen temperature stabilized at 430⁰ C. The rider was then loaded against the rotating disk.

RESULTS AND DISCUSSION

The materials and lubricants studied in this program were selected either because they are currently in use for sliding mechanisms of supersonic aircraft (aluminum bronze and acrylic-bonded MoS₂) or because they are candidate alternative materials (cast Inconel (600) and silicone (Mil L25681C)). Since tin has been successfully used as a component in many bearing materials, it was selected as an alloying element with titanium and copper for this program. These commercial materials are described in table I.

Figure 2 shows the wear and friction coefficient of the two presently used aluminum bronzes and the alternative, cast Inconel. As can be seen, the cast Inconel had significantly lower wear and slightly lower friction. Equally important from the long-term standpoint is the surface damage to the materials. As shown in figure 3, both the aluminum bronze and the cast Inconel have a tendency to gall. The wear tracks (on the disks) show evidence of abrasive wear in the form of fine grooves about 40 to 50 micrometers deep and 10 to 20 micrometers wide. There is evidence of a copper-color transfer film, which is less than 1 micrometer thick.

Three Approaches to Reducing Wear

Three surface treatments commonly used to reduce surface damage were investigated. These treatments were applied to the disk surface only. The first method was to apply a thin brush-coated layer of acrylic-bonded MoS₂. The second method was to brush on a layer of MoS₂ and silicone grease (grease consistency). The third method

was to harden the disk surface by forming a titanium diboride (TiB_2) conversion coating. The results are shown in figure 4. The data reveal that all three of the methods significantly increased the wear rate of the aluminum bronze riders. The higher wear resulted from the abrasive action of the decomposition products of the treatments. With the acrylic-bonded MoS_2 the increased wear resulted from the formation of molybdenum trioxide (MoO_3), which is still abrasive at 430°C . With the silicone grease and MoS_2 the condition was compounded by the silicone dioxide (SiO_2) resulting from the decomposition of the silicone. The TiB_2 conversion coating increased rider wear by the abrasiveness of the hard asperities on the disk surface. This was probably augmented by the abrasive action of boron oxide (B_2O_3).

The lower friction observed with the acrylic-bonded MoS_2 most likely resulted from the lubricating effect of the carbon residue from the decomposed acrylic lacquer.

Figure 5 shows the wear surfaces after 5.5 hours of sliding with the MoS_2 coatings. The disk run with the acrylic-bonded MoS_2 does not show significant surface damage (the lapping marks are still visible), which indicates that the surface was protected by the carbonized acrylic lacquer. The surface was not protected by the silicone grease and MoS_2 , but was abraded by the SiO_2 residue.

Experimental Titanium-Tin and Copper-Tin Alloys

Since tin has long been used as a constituent in bearing alloys, three titanium-tin (Ti-Sn) alloys were also included in this program. In addition to being a lubricant, tin ($>5\text{ wt.}\%$) also hardens titanium (ref. 13). Wear and friction of a commercial alloy (2.5 wt.% Sn) and two experimental alloys (10 and 20 wt.% Sn) are shown in figure 6. The 10- and 20-weight-percent-tin alloys have a single-phase microstructure (hexagonal close packed). This structure should result in alloys with good friction and wear properties (ref. 2). The alloy containing 2.5 weight percent tin had a much higher wear rate than that of the aluminum bronzes, but did not show the surface damage exhibited by the aluminum bronzes. The lack of improvement in wear of the 2.5-weight-percent-tin alloy would be expected on the basis of results for low-tin alloys reported in reference 13. Wear rates of the 10- and 20-weight-percent-tin alloys were about two orders of magnitude lower than that for the 2.5-weight-percent-tin alloy and one order of magnitude lower than that for the presently used aluminum bronze. As is common with tin alloys in sliding contact, a transfer film was formed on the mating surface. The lower wear of the 10- and 20-weight-percent-tin alloys resulted from the increase in hardness by the tin (ref. 13) as well as from the film forming capability of the alloy. Transfer films on the disk surface were 40 micrometers thick and completely covered the lapping marks. Figure 6(b) shows that the friction coefficient of the

tin alloys was similar to that of the aluminum bronzes (fig. 2(b)). Figure 7 shows the wear surfaces of two of the tin alloys. Note the heavy transfer films. It is also apparent that there was back transfer of material (from disk to rider) with the 20-weight-percent-tin alloy.

Also included in this program were three copper alloys, to determine if dissimilar metals would reduce the friction. The copper - 10-percent-tin alloy (Cu-10Sn) and the copper - 20-percent-silver alloy (Cu-20Ag) had wear rates similar to those of the aluminum bronzes (fig. 8(a)). The copper - 30-percent-tin alloy (Cu-30Sn) had a wear rate almost an order of magnitude lower than those of the aluminum bronzes. The friction coefficient was about the same as those of the aluminum bronzes (fig. 8(b)). A nickel alloy described by the manufacturer as nongalling (fig. 9) also showed a wear rate that was considerably lower than those of the aluminum bronzes but no reduction in friction coefficient.

Boridizing of Titanium-Aluminum-Vanadium Disk Surface

The four alloys showing the lowest rate were next run against Ti-6Al-4V with the TiB_2 conversion coating to determine if the harder surface would further reduce the wear rate. The wear rate was higher by one to three orders of magnitude. Examination of wear tracks indicated that the previous thick ($40\text{-}\mu\text{m}$) transfer films were not present, which helped to explain the high wear rates. Transfer films are generally essential to low wear rates. Figure 9(b) shows that the friction coefficients with the TiB_2 coating were still above 0.2. Although the friction coefficients for the tin-containing alloys were not lower than those of the aluminum bronzes, the friction traces were much smoother.

All the alloys containing less than 10 weight percent tin produced wear debris (fine black powder), which analysis showed to be titanium.

These experiments indicate that, although high-tin alloys have lower wear rates than the aluminum bronzes when sliding against Ti-6Al-4V, they do not have lower friction coefficients. Also, the use of coatings and/or treatments which inhibit the formation of a transfer film (e.g., copper or tin) results in high wear rates.

In addition to low friction and wear, a candidate material for an aircraft application should have low weight. Of the three materials suggested as replacement materials (#23 nickel alloy, Ti-20Sn, and Cu-30Sn), only the nickel alloy is denser than the presently used aluminum bronzes (see table II). This nickel alloy is only slightly denser than the cast Inconel (600) material (which has a similar wear rate but has a greater tendency to gall).

These experiments indicate that the galling tendencies and wear rate of Ti-20Sn

were significantly lower than those of the presently used aluminum bronzes. The friction coefficient of Ti-20Sn was below 0.35.

SUMMARY OF RESULTS

Experiments conducted with various alloys sliding against a titanium - 6-percent-aluminum - 4-percent-vanadium alloy (Ti-6Al-4V) in 430° C air at a velocity of 13 centimeters per second and a load of 250 grams revealed that

1. The wear of titanium - 10-percent-tin, titanium - 20-percent-tin, and copper - 30-percent-tin alloys in sliding contact with Ti-6Al-4V was significantly lower than that of aluminum bronze, which is a conventional bearing material. The tin-containing alloys also had little or no tendency to gall or seize.

2. The friction coefficient of all the alloys run in this program was about 0.25.

3. The conventional methods of coating aluminum bronze with bonded molybdenum disulfide (MoS_2) were ineffective in reducing wear and galling of alloys in sliding contact with Ti-5Al-4V under the conditions of these tests. This result was expected because of the poor thermal stability of MoS_2 and binders at the test temperature (430° C).

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, February 5, 1976,

506-16.

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TABLE I. - COMPOSITIONS OF COMMERCIAL MATERIALS USED IN
THIS PROGRAM

Material	Composition, wt. %
Cu-10Al	10.5 Al, 3.5 Fe, 0.7 other, bal. Cu
Cu-13Al	13.1 Al, 4.4 Fe, 0.7 other, bal. Cu
#23 Nickel	78 Ni, 4 Pb, 8 Sn, 7.5 Zn, 2 Mn, 0.5 other
Cast Inconel (600)	15.8 Cr, 7.2 Fe, 0.2 Mn, 0.2 Si, 0.1 Cu, bal. Ni
Ti-6Al-4V	6 Al, 4 V, bal. Ti
Acrylic MoS ₂	20 MoS ₂ , bal. acrylic lacquer
Mil-L25681C	50 MoS ₂ , 50 silicone grease

TABLE II. - DENSITY OF ALLOYS USED
IN PROGRAM

Material	Density, g/cm ³	Density relative to Cu-10Al
Cu-10Al	7.27	1.0
Cu-13Al	6.97	.96
#23 Nickel	8.79	1.21
Cast Inconel (600)	8.43	1.16
Ti-6Al-4V	4.47	.61
Ti-20Sn	4.94	.68
Cu-30Sn	6.68	.92

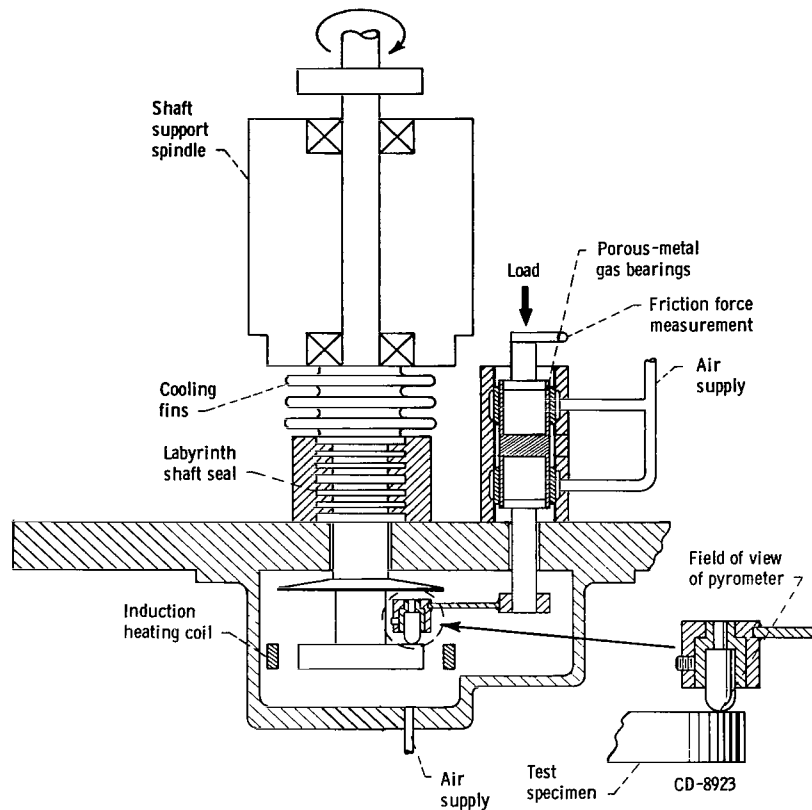


Figure 1. - Friction and wear test apparatus.

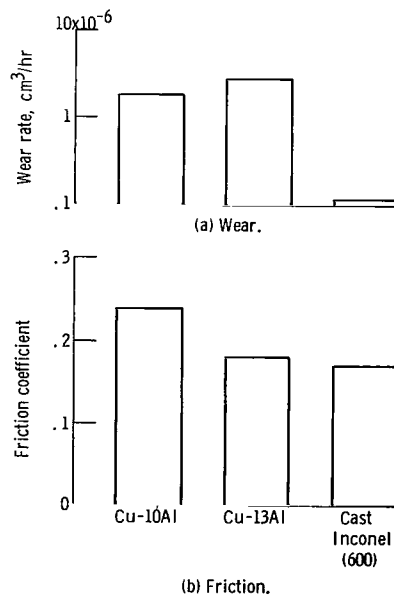


Figure 2. - Wear and friction of baseline alloys sliding against Ti-6Al-4V in air at 430°C . Load, 250 grams; sliding velocity, 13 centimeters per second.

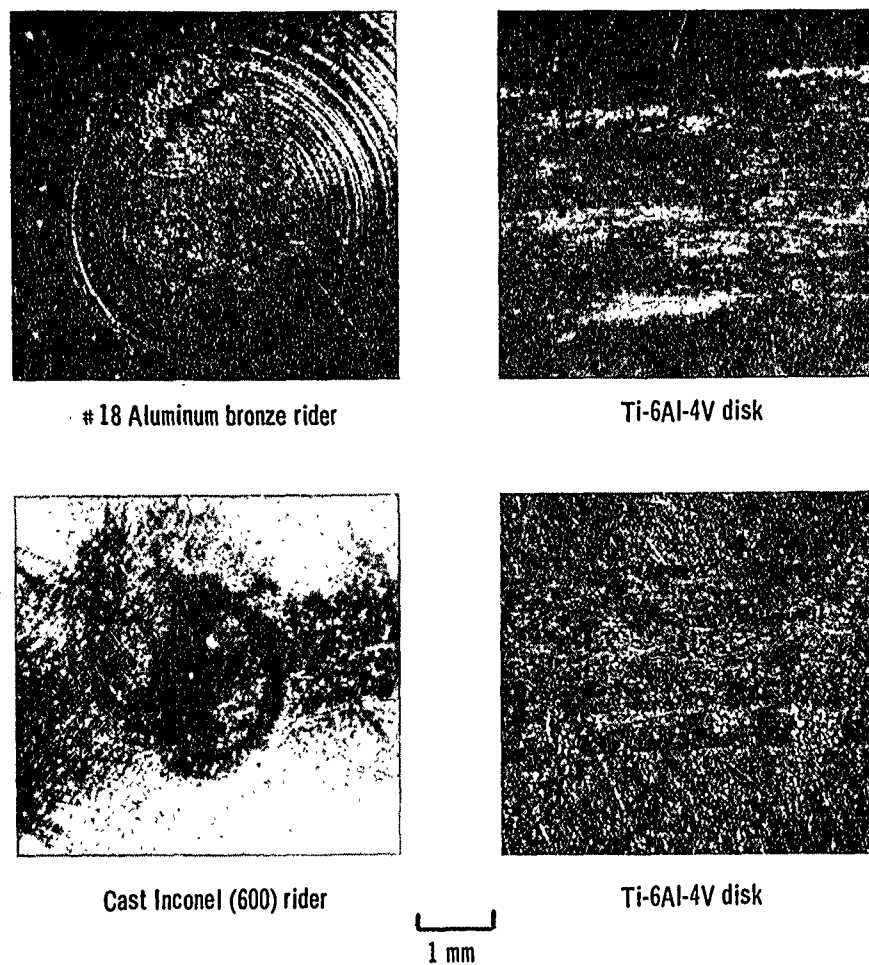


Figure 3. - Wear surfaces of bronze and Inconel (600) riders and Ti-6Al-4V disks after sliding in air at 430° C. Load, 250 grams; sliding velocity, 13 centimeters per second; test duration, 6 hours.

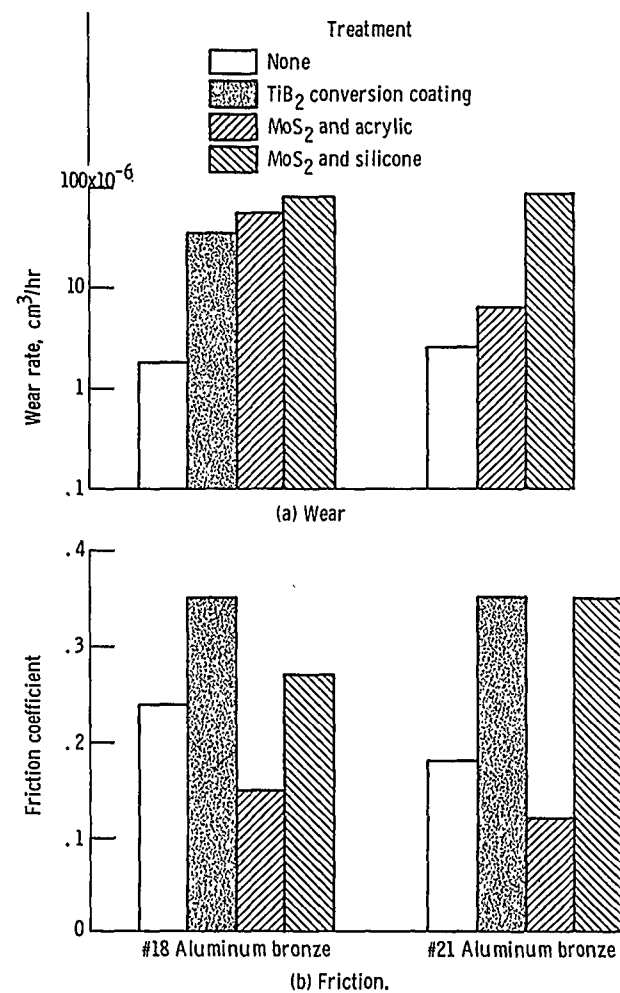
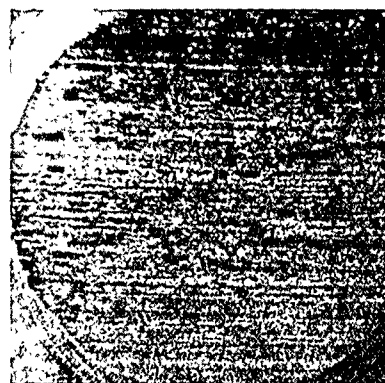
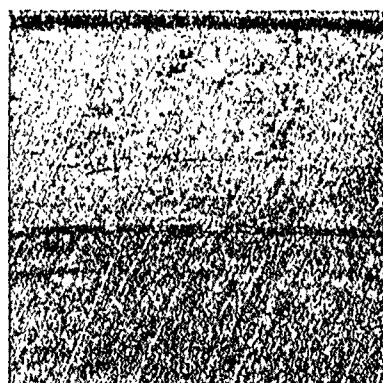


Figure 4. - Wear and friction of two bronzes after sliding against treated Ti-6Al-4V in air at 430° C. Load, 250 grams; sliding velocity, 13 centimeters per second.



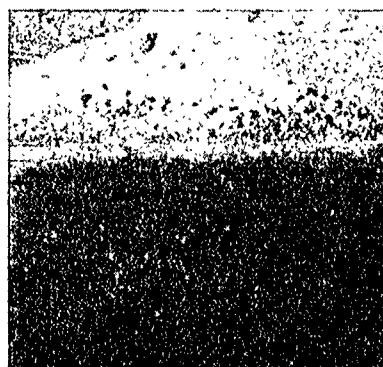
#18 Aluminum bronze rider



Acrylic-bonded MoS₂ on Ti-6Al-4V disk



#18 Aluminum bronze rider



Silicone grease and MoS₂ on Ti-6Al-4V disk

1 mm

Figure 5. - Wear surfaces of bronze riders and treated Ti-6Al-4V disks after sliding in air at 430°C. Load, 250 grams; sliding velocity, 13 centimeters per second; test duration, 5.5 hours.

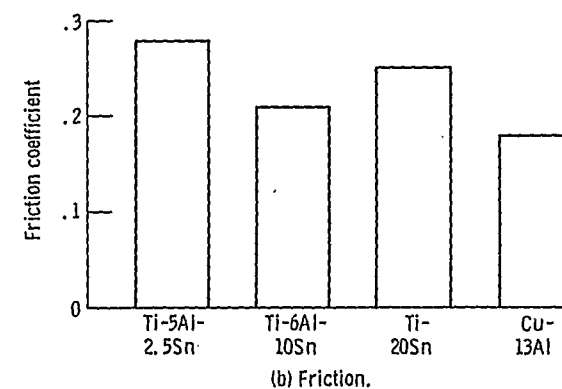
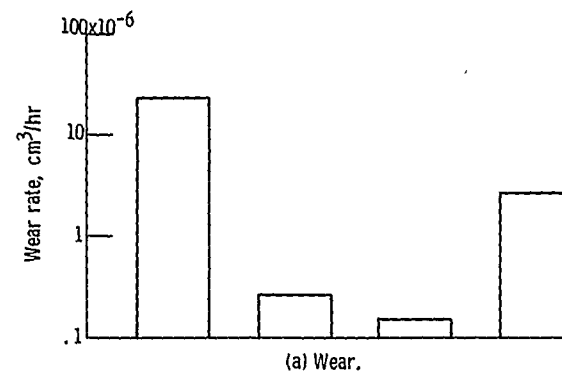
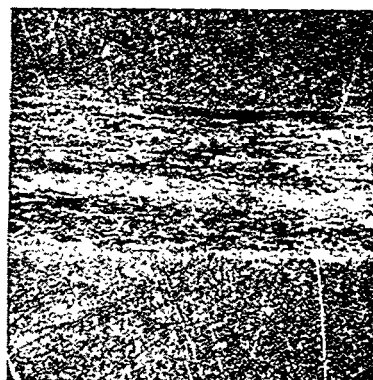


Figure 6. - Wear and friction of titanium alloys sliding against Ti-6Al-4V in air at 430°C. Load, 250 grams; sliding velocity, 13 centimeters per second.



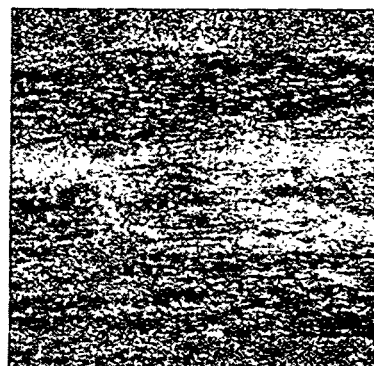
Ti-2.5Sn-5Al rider



Ti-6Al-4V disk



Ti-20Sn rider



Ti-6Al-4V disk

1 mm

Figure 7. - Wear surfaces of Ti-2.5Sn-5Al and Ti-20Sn riders and Ti-6Al-4V disks after sliding in air at 430°C. Load, 250 grams; sliding velocity, 13 centimeters per second; test durations, 4 and 5.5 hours, respectively.

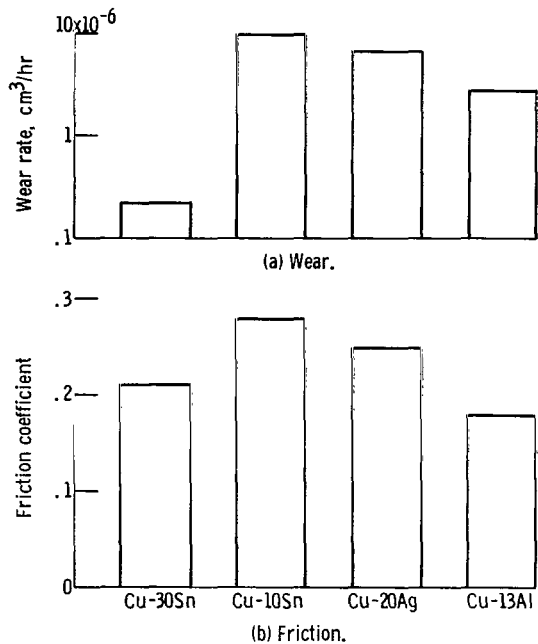


Figure 8. - Wear and friction of copper alloys sliding against Ti-6Al-4V in air at 430°C . Load, 250 grams; sliding velocity, 13 centimeters per second.

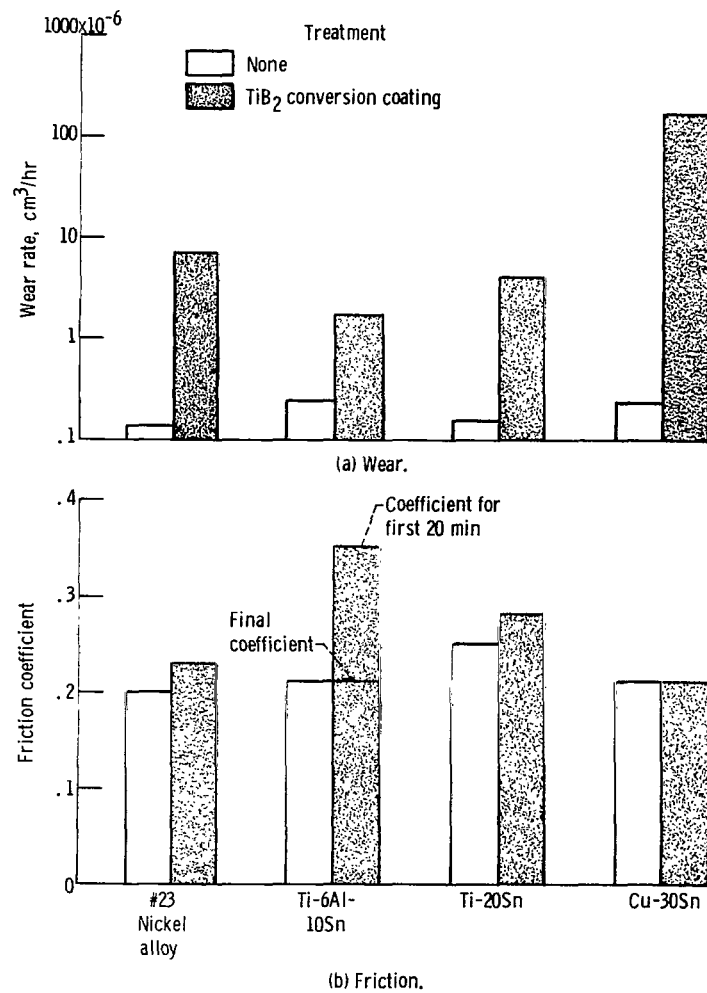


Figure 9. - Wear and friction of selected alloys sliding against Ti-6Al-4V treated with TiB₂ conversion coating in air at 430°C . Load, 250 grams; sliding velocity, 13 centimeters per second.

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